8 Energy production

Learning objectives

- Solve problems with specific energy and energy density.
- Distinguish between primary and secondary energy sources and renewable and non-renewable energy sources.
- Describe fossil fuel power stations, nuclear power stations, wind generators, pumped storage hydroelectric systems, solar power cells and solar panels.
- Solve problems involving energy transformations in the systems above.

8.1 Energy sources

This section discusses energy sources and ways to produce power.

Primary and secondary energy

Primary energy is energy found in nature that has not yet been subject to processing of any kind. Examples include the energy stored in **fuels** such as crude oil, coal and natural gas, as well as solar energy, wind energy and so on. When primary energy is processed or exploited **secondary energy** is produced. Secondary energy must be suitable for use in machines which perform mechanical work; it could also be a very versatile form of energy such as electricity. To give one example, the kinetic energy of particles of air in wind is primary energy. A simple windmill can extract some of this kinetic energy and perform mechanical work as it raises water from a well; or, the kinetic energy of the wind can be used to turn a generator producing electricity. In both cases we have primary energy being transformed to secondary energy.

How much energy can be extracted from a fuel defines the fuel's specific energy and energy density. **Specific energy**, E_S, is the amount of energy that can be extracted from a unit mass of fuel; it is measured in $\mathrm{J\,kg^{-1}}$. **Energy density**, E_D, is the amount of energy that be extracted from a unit volume of fuel; it is measured in $\mathrm{J\,m^{-3}}$. Table **8.1** gives the values for E_S and E_D for some common fuels.

Worked example

8.1 **a** Show that $E_D = \rho E_S$ where ρ is the density of the fuel.
b Use Table **8.1** to estimate the density of uranium-235.

a E_D is the amount of energy that be extracted from a unit volume of fuel, so:

$$E_D = \frac{Q}{V}$$

where Q is the energy released from volume V.

Using the definition of density ρ as mass per unit volume, a volume V has mass m given by:

$$m = V\rho$$

$$\Rightarrow V = \frac{m}{\rho}$$

Then, $E_D = \dfrac{Q}{m/\rho} = \dfrac{Q}{m} \times \rho = \rho E_S$

b Table **8.1** gives values for E_D and E_S for uranium-235. Hence:

$$\rho = \frac{E_D}{E_S} = \frac{1.3 \times 10^{18}}{70 \times 10^{12}} \approx 2 \times 10^4\, \text{kg m}^{-3}.$$

Fuel	Specific energy E_S / J kg^{-1}	Energy density E_D / J m^{-3}
uranium-235	7.0×10^{13}	1.3×10^{18}
hydrogen	1.4×10^{8}	1.0×10^{7}
natural gas	5.4×10^{7}	3.6×10^{7}
gasoline	4.6×10^{7}	3.4×10^{10}
kerosene	4.3×10^{7}	3.3×10^{10}
diesel	4.6×10^{7}	3.7×10^{10}
coal	3.2×10^{7}	7.2×10^{10}

Table 8.1 Specific energy or energy density of fossil fuels.

Specific energy or energy density are major considerations in the choice of a fuel. Obviously, all other factors being equal, the higher the specific energy or energy density, the more desirable the fuel.

We may classify energy sources into two large classes, **non-renewable** and **renewable**.

Non-renewable sources of energy are finite sources, which are being depleted much faster than they can be produced and so will run out. They include fossil fuels (e.g. oil, natural gas and coal) and nuclear fuels (e.g. uranium).

Renewable sources include solar energy (and the other forms indirectly dependent on solar energy, such as wind energy and wave energy) and tidal energy. In principle, they will be available as long as the Sun shines and that means billions of years.

The main sources of energy, and the percentage of the total energy produced of each, is given in Table **8.2**. The figures are world averages for 2011 and are approximate.

Fuel	Percentage of total energy production / %	Carbon dioxide emission / g MJ^{-1}
oil	32	70
natural gas	21	50
coal	27	90
nuclear	6	–
hydroelectric	2	–
biofuels	10	–
others	<2	–

Table 8.2 Energy sources and the percentage of the total energy production for each. The third column gives the mass of carbon dioxide emitted per unit of energy produced from a particular fuel. Fossil fuels account for about 80% of the total energy production.

Fossil fuels

Fossil fuels (oil, coal and natural gas) have been created over millions of years. They are produced by the decomposition of buried animal and plant matter under the combined action of the high pressure of the material on top and bacteria.

Burning coal and oil have been the traditional ways of producing electricity. A typical fossil fuel power plant is shown in Figure **8.1**.

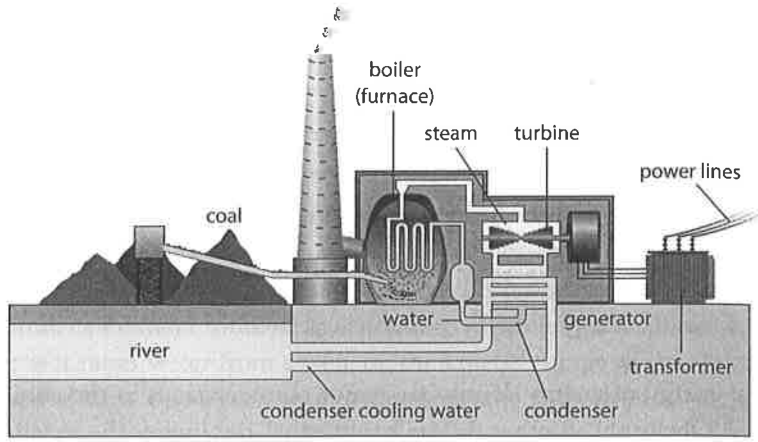


Figure 8.1 A coal-burning power plant.

Burning coal produces energy that turns water into steam in boilers. The pressurised steam forces a turbine to turn. The turbine makes the coils of a generator rotate in a magnetic field, creating electricity by electromagnetic induction (see Subtopic **11.2**). Cold water (usually from a nearby river) condenses the steam into liquid water that can again be heated in the boilers. Figure **8.2** shows a Sankey diagram for this plant.

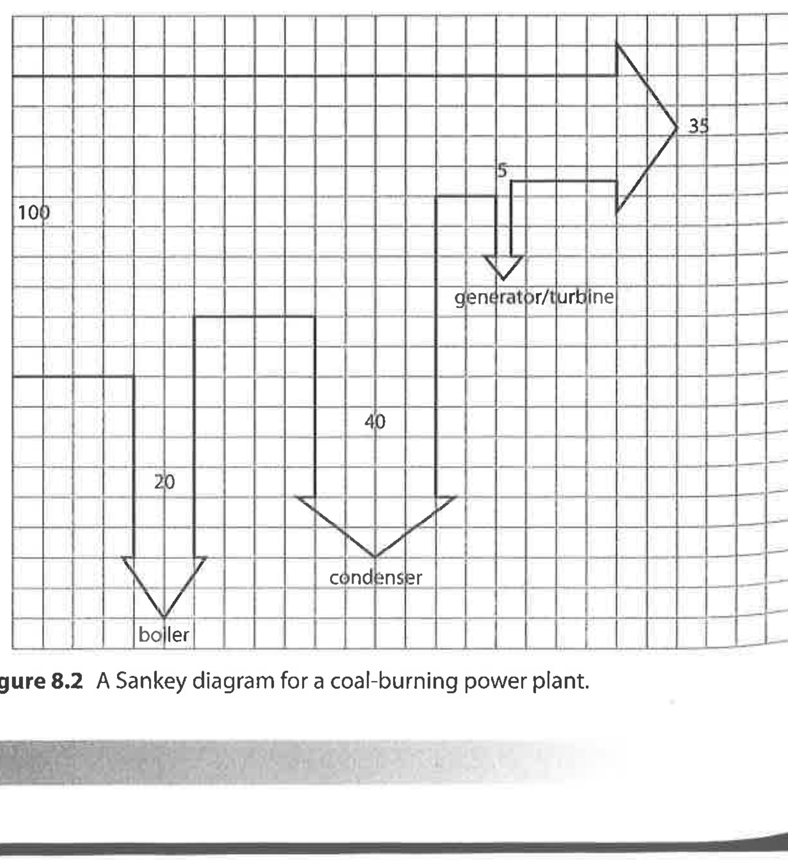


Figure 8.2 A Sankey diagram for a coal-burning power plant.

A **Sankey diagram** is an arrow block diagram representing energy flows. The width of the arrow is proportional to the amount of energy being transferred. Here, 100 units of energy created by the burning of coal enter the system. Twenty units are lost though the boilers, and an additional 40 units are lost as steam condenses into water. Of the remaining 40 units, about five are lost because of friction in the turning turbine and generator. In the end, only 35 units of energy have been produced as electricity. The efficiency, e, is defined by:

$$e = \frac{\text{useful power}}{\text{input power}}$$

The efficiency of this power plant is:

$$e = \frac{35}{100} = 0.35 \quad \text{or} \quad 35\%$$

Although reasonably efficient, fossil fuel power plants are primarily responsible for atmospheric pollution and contribute greenhouse gases to the atmosphere (Figure **8.3**). (Greenhouse gases and the greenhouse effect are discussed in Subtopic **8.2**.)

Natural gas power plants have higher efficiencies, reaching almost 60%, and have much smaller greenhouse gas emissions.

Power is energy per unit time, i.e.

$$\text{power} = \frac{\text{energy}}{\text{time}}$$

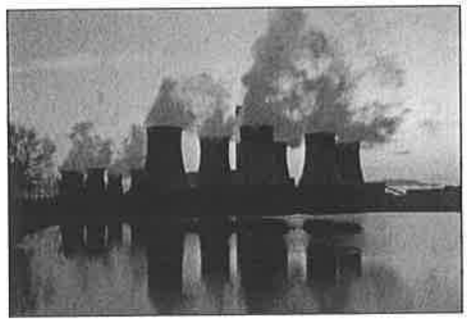


Figure 8.3 Fossil fuels produce pollution and greenhouse gases.

Worked example

8.2 A power plant produces electricity by burning coal. The thermal energy produced is used as input to a steam engine, which makes a turbine turn, producing electricity. The plant has a power output of 400 MW and operates at an overall efficiency of 35%.

a Calculate the rate at which thermal energy is provided by the burning coal.

b Calculate the rate at which coal is burned (use a coal specific energy of $30\,\text{MJ}\,\text{kg}^{-1}$).

c The thermal energy discarded by the power plant is removed by water (Figure **8.4**). The temperature of the water must not increase by more than 5 °C. Calculate the rate at which the water must flow.

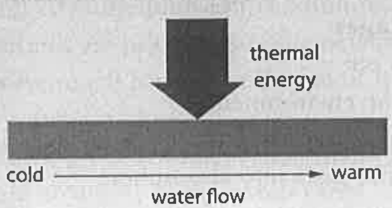


Figure 8.4

a The efficiency is the ratio of useful power output to power input. So:

$$0.35 = \frac{\text{power output}}{\text{power input}} = \frac{400\,\text{MW}}{P_{\text{input}}}$$

$$\Rightarrow P_{\text{input}} = \frac{400}{0.35} = 1.14 \times 10^3 \approx 1.1 \times 10^3\,\text{MW}$$

b Each kilogram of coal provides 30 MJ, which is 30×10^6 J . The power input is 1.14×10^3 MW, which is $1.14\times10^9\,\mathrm{J\,s^{-1}}$.

So the mass of coal that must be burned per second, $\frac{\Delta m}{\Delta t}$, is found from:

$$\frac{\Delta m}{\Delta t}\times30\times10^6=1.14\times10^9$$

$$\Rightarrow\ \frac{\Delta m}{\Delta t}=38\,\mathrm{kg\,s^{-1}}$$

This is equivalent to:

$$38\times60\times60\times24\times365=1.2\times10^9\,\mathrm{kg\,yr^{-1}}$$

c The thermal energy discarded is the difference between the energy produced by burning the coal and the useful energy output. So:

rate at which thermal energy is discarded = rate at which energy enters the water $\left(\frac{\Delta Q}{\Delta t}\right)$

$$=1140-400=740\,\mathrm{MW}$$

This thermal energy warms up the water according to:

$$Q=(\Delta m)c\Delta T$$

where m is the mass of water into which the thermal energy goes, c is the specific heat capacity of water ($4200\,\mathrm{J\,kg^{-1}K^{-1}}$) and ΔT is the temperature increase of the water (5 °C).

Rearranging, the rate at which thermal energy enters the water is then:

$$\frac{\Delta Q}{\Delta t}=\frac{\Delta m}{\Delta t}\times c\Delta T=740\,\mathrm{MW}$$

Therefore:

$$\frac{\Delta m}{\Delta t}=\frac{740\times10^6}{c\Delta T}=\frac{740\times10^6}{4200\times5}$$

$$\frac{\Delta m}{\Delta t}=35\times10^3\,\mathrm{kg\,s^{-1}}$$

The water must flow at a rate of $35\times10^3\,\mathrm{kg\,s^{-1}}$.

Exam tip: Fossil fuels

Advantages

- Relatively cheap (while they last)
- High power output (high energy density)
- Variety of engines and devices use them directly and easily
- Extensive distribution network is in place

Disadvantages

- Will run out
- Pollute the environment
- Contribute to greenhouse effect by releasing greenhouse gases into atmosphere

In the overall considerations over choice of fuel, it is necessary to take into account the cost of transporting the fuel from its place of production to the place of distribution. Fossil fuels have generally high costs because the mass and volume of the fuel tend to be large. Similarly, extensive storage facilities are needed. Fossil fuels, especially oil, pose serious environmental problems due to leakages at various points along the production–distribution line.

Nuclear power

A nuclear reactor is a machine in which nuclear fission reactions take place, producing energy. Fission reactions were discussed in Subtopic **7.2**.

Schematic diagrams of the cores of two types of nuclear reactor are shown in Figure **8.5**.

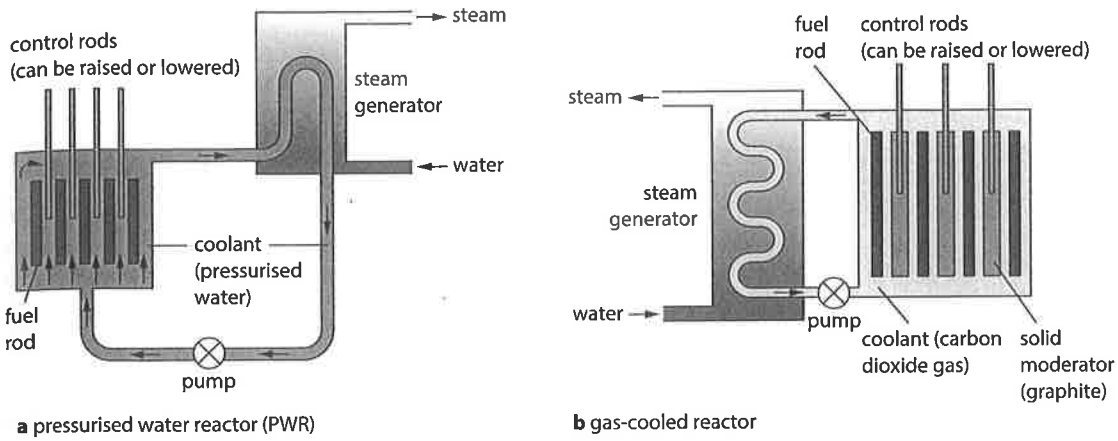


Figure 8.5 Schematic diagrams of two types of fission reactor.

The **fuel** of a nuclear reactor is typically uranium-235. In **induced** fission neutrons initiate the reaction. One possible fission reaction is:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2^{1}_{0}n$$

The neutrons produced can be used to collide with other nuclei of uranium-235 in the reactor, producing more fission, more energy and more neutrons. The reaction is thus self-sustaining; it is called a **chain reaction**. For the chain reaction to get going, a certain minimum mass of uranium-235 must be present, otherwise the neutrons escape without causing further reactions. This minimum mass is called the **critical mass** (for pure uranium-235, this is about 15 kg and rises to 130 kg for fuels containing 10% uranium-235). Uranium-235 will only capture neutrons if the neutrons are not too fast. The neutrons produced in the fission reactions are much too fast, and so must be slowed down before they can initiate further reactions.

The slowing down of neutrons is achieved through collisions of the neutrons with atoms of the **moderator**, the material surrounding the **fuel rods** (the tubes containing uranium). The moderator material can be graphite or water, for example. As the neutrons collide with moderator atoms, they transfer energy to the moderator, increasing its temperature. A **heat exchanger** is therefore needed to extract the heat from the moderator. This can be done using cold water that circulates in pipes throughout the moderator. The water is turned into steam at high temperature and pressure. The steam is then used to turn the turbines of a generator, finally producing electricity.

The rate of the reactions is determined by the number of neutrons available to be captured by uranium-235. Too few neutrons would result

in the reaction stopping, while too many neutrons would lead to an uncontrollably large release of energy. Thus **control rods** are introduced into the moderator. These absorb neutrons when too many neutrons are present thus decreasing the rate of reactions. If the rate of reactions needs to be increased, the control rods are removed.

Worked example

8.3 As discussed in Subtopic **7.2**, one kilogram of uranium-235 releases a quantity of energy equal to 70×10^{12} J. Natural uranium (mainly uranium-238) contains about 0.7% of uranium-235 (by mass). Calculate the specific energy of natural uranium.

One kilogram of natural uranium contains 0.7% of uranium-235 and so the specific energy E_S of natural uranium as a nuclear fuel is:

$$E_S = \frac{0.7}{100} \times 70 \times 10^{12} = 4.9 \times 10^{11}\,\text{J kg}^{-1}$$

$$E_S = 490\,\text{GJ kg}^{-1}$$

This value is substantially higher than for fossil fuels.

Risks with nuclear power

The fast neutrons produced in a fission reaction may be used to bombard uranium-238 and produce plutonium-239. The reactions leading to plutonium production are:

$$^{1}_{0}\text{n} + ^{238}_{92}\text{U} \rightarrow ^{239}_{92}\text{U}$$

$$^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e} + \bar{\nu}$$

$$^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e} + \bar{\nu}$$

The importance of these reactions is that non-fissionable material (uranium-238) is being converted to fissionable material (plutonium-239) as the reactor operates. The plutonium-239 produced can then be used as the nuclear fuel in other reactors. It can also be used in the production of nuclear weapons, which therefore raises serious concerns.

The spent fuel in a nuclear reactor, together with the products of the reactions, are all highly radioactive with long half-lives. Properly disposing of this material is a serious problem of the fission process. At present, this material is buried deep underground in containers that are supposed to avoid leakage to the outside. In addition, there is always the possibility of an accident due to uncontrolled heating of the moderator, which might start a fire or explosion. This would be a conventional explosion – the reactor cannot explode in the way a nuclear weapon does. In the event of an explosion, radioactive material would leak from the sealed core of

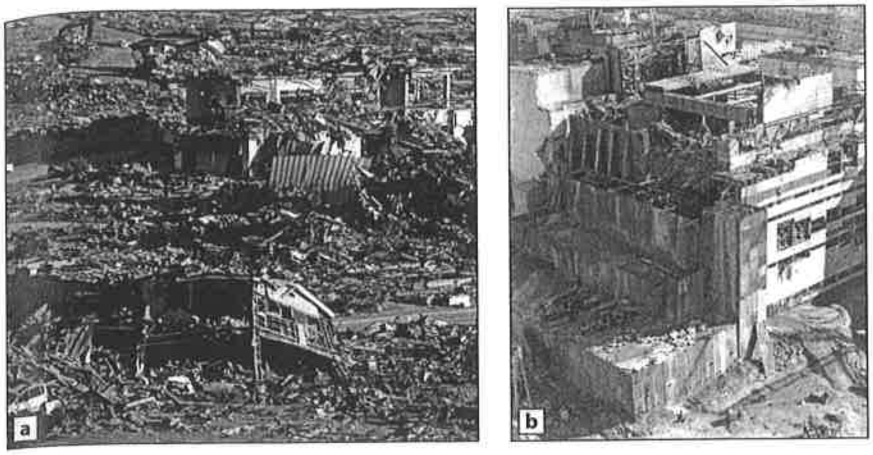


Figure 8.6 The effects of two of the world's worst nuclear accidents. **a** The nearby devastation after the explosion at the Fukushima nuclear plant in Japan on 11 March 2011. **b** Reactor number 4 in the Chernobyl nuclear power plant after the explosion on 26 April 1986.

a reactor, dispersing radioactive material into the environment. Both the explosions shown in Figure **8.6** resulted in widespread contamination. Even worse, we may have the meltdown of the entire core, as in the 1986 accident at Chernobyl.

These are serious concerns with nuclear fission as a source of commercial power. On the positive side, nuclear power does not produce greenhouse gases.

Exam tip: Nuclear power

Advantages

- High power output
- Large reserves of nuclear fuels
- Nuclear power stations do not produce greenhouse gases

Disadvantages

- Radioactive waste products difficult to dispose of
- Major public health hazard should 'something go wrong'
- Problems associated with uranium mining
- Possibility of producing materials for nuclear weapons

Worked example

8.4 A nuclear power plant produces 800 MW of electrical power with an overall efficiency of 35%. The energy released in the fission of one nucleus of uranium-235 is 170 MeV. Estimate the mass of uranium used per year.

Let P be the power produced from nuclear fission. Since the efficiency is 35%, then:

$$0.35 = \frac{800}{P}$$

$$\Rightarrow P = 2286\,\text{MW}$$

The energy produced in one year is:

$$2286 \times 10^6 \times 365 \times 24 \times 3600 = 7.21 \times 10^{16}\,\text{J}$$

The energy produced in the fission of one nucleus is:

$$170 \times 10^6 \times 1.6 \times 10^{-19} = 2.72 \times 10^{-11}\,\text{J}$$

and so the number of fission reactions in a year is:

$$\frac{7.21 \times 10^{16}}{2.72 \times 10^{-11}} = 2.65 \times 10^{27}$$

The mass of uranium-235 used up in a year is therefore $2.65 \times 10^{27} \times 235 \times 1.66 \times 10^{-27}$, which is about 1000 kg.

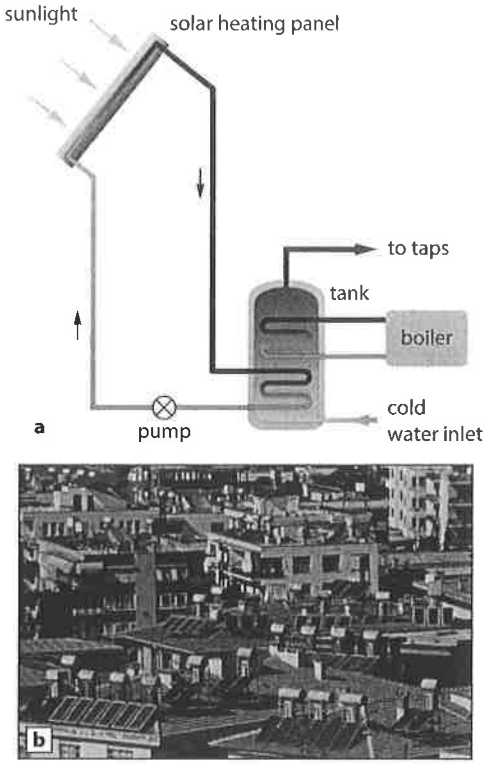


Figure 8.7 **a** A solar heating panel to provide warm water to a house. **b** Solar heating panels on roofs of apartment buildings.

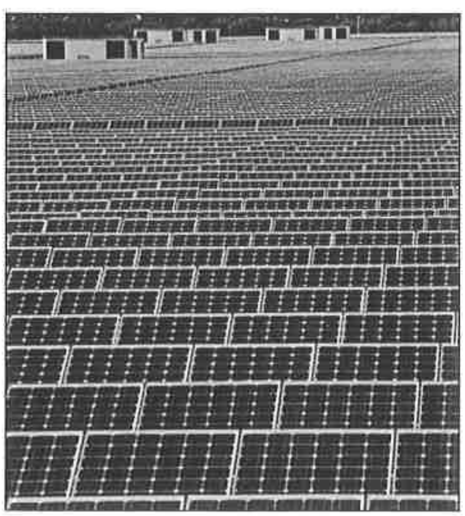


Figure 8.8 To produce appreciable amounts of electrical power very many photovoltaic cells are needed.

Solar power

The nuclear fusion reactions in the Sun send out an incredible, and practically inexhaustible, amount of energy, at a rate of about 3.9×10^{26} W. The Earth receives about 1400 W m^{-2} at the outer atmosphere. About 1000 W m^{-2} (1 kW m^{-2}) reaches the surface of the Earth. This amount assumes direct sunlight on a clear day and thus is the maximum that can be received at any one time. This is high-quality, free and inexhaustible energy that can be put to various uses.

Solar panels

An early application of solar energy has been in what are called 'active solar devices'. In these, sunlight is used directly to heat water or air for heating in a house, for example. The collecting surface is usually flat and covered by glass for protection; the glass should be coated to reduce reflection. A blackened surface below the glass collects sunlight, and water circulating in pipes underneath is heated. This hot water can then be used to heat water for use in the house (the heated water is kept in well-insulated containers). The general setup is shown in Figure **8.7a**. An additional boiler is available to heat the water in days with little sunlight.

These simple collectors are cheap and are usually put on the roof of a house (Figure **8.7b**). Their disadvantage is that they tend to be bulky and cover too much space.

Photovoltaic cells

A promising method for producing electricity from sunlight is that provided by **photovoltaic cells** (Figure **8.8**). The photovoltaic cell was developed in 1954 at Bell Laboratories and was used extensively in the space programme. A photovoltaic cell converts sunlight directly into direct current (dc) at an efficiency approaching 30%. Sunlight incident on the cell releases electrons and establishes a potential difference across the cell.

These systems can usefully be used to power small remote villages, pump water in agriculture, power warning lights, etc. Their environmental ill-effects are practically zero, with the exception of chemical pollution at the place of their manufacture.

Exam tip: Solar power

Advantages

- 'Free'
- Inexhaustible
- Clean

Disadvantages

- Works during the day only
- Affected by cloudy weather
- Low power output
- Requires large areas
- Initial costs high

Worked example

8.5 The average intensity of solar radiation incident on the Earth surface is $245\,\mathrm{W\,m^{-2}}$. In an array of photovoltaic cells, solar energy is converted into electrical energy with an efficiency of 20%. Estimate the area of photovoltaic cells needed to provide 2.5 kW of electrical power.

The power incident on an area $A\,\mathrm{m^2}$ is $245 \times A$.

As the cells are 20% efficient, the electrical power P provided by area A of cells is:

$$P = 0.20 \times 245 \times A$$

The power required is 2500 W.

$$2500 = 0.20 \times 245 \times A$$

$$\Rightarrow A = 51\,\mathrm{m^2}$$

The area of photovoltaic cells needed to provide 2.5 kW of electrical power is $51\,\mathrm{m^2}$.

Hydroelectric power

Hydroelectric power, the power derived from moving water masses, is one of the oldest and most established of all renewable energy sources (Figure **8.9**).

Hydroelectric power stations are associated with massive changes in the ecology of the area surrounding the plants. To create a reservoir behind a newly constructed dam, a vast area of land must be flooded.

The principle behind hydropower is simple. Consider a mass m of water that falls down a vertical height h (Figure **8.10**). The potential energy of

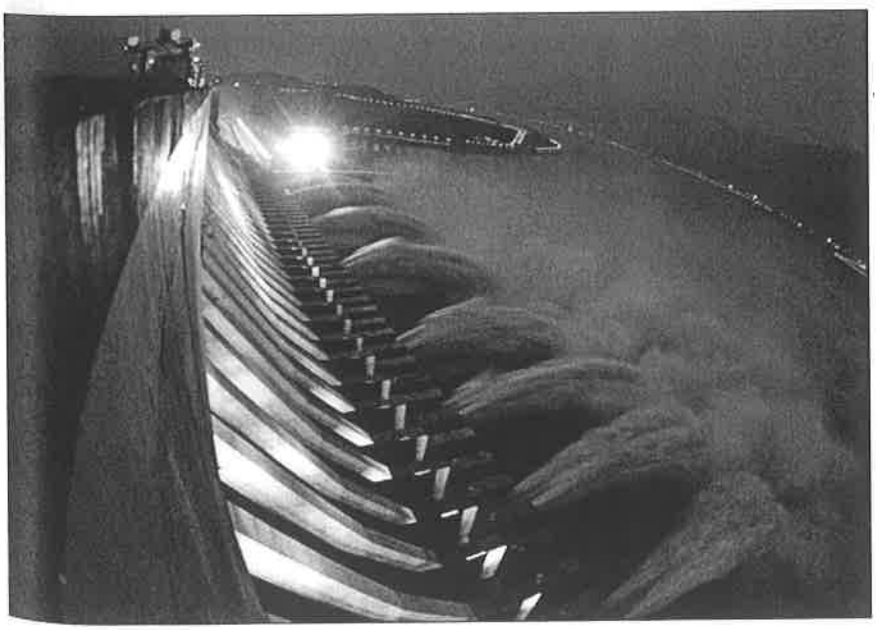


Figure 8.9 The Three Gorges Dam spanning the Yangtze River in Hubei province in China.

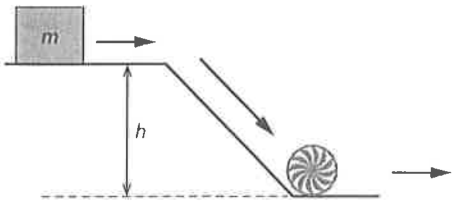


Figure 8.10 Water falling from a vertical height h has its potential energy converted into kinetic energy, which can be used to drive turbines.

Exam tip: Hydroelectric power

Advantages

- 'Free'
- Inexhaustible
- Clean

Disadvantages

- Very dependent on location
- Requires drastic changes to environment
- Initial costs high

the mass is mgh, and this is converted into kinetic energy when the mass descends the vertical distance h. The mass of the water is given by $\rho\Delta V$, where ρ is the density of water (1000 kg m^{-3}) and ΔV is the volume it occupies.

The rate of change of this potential energy, i.e. the power P, is given by the change in potential energy divided by the time taken for that change. So:

$$P = \frac{mgh}{\Delta t} = \frac{(\rho\Delta V)gh}{\Delta t} = \rho\frac{\Delta V}{\Delta t}gh$$

The quantity $Q = \frac{\Delta V}{\Delta t}$ is known as the volume flow rate (volume per second) and so:

$$P = \rho Qgh$$

This is the power available for generating electricity (or to convert into some other mechanical form) and it is thus clear that hydropower requires large volume flow rates, Q, and large heights, h.

Worked example

8.6 Find the power developed when water in a stream with a flow rate $50 \times 10^{-3}\,m^3 s^{-1}$ falls from a height of 15 m.

Applying the power formula, we find:

$$P = \rho Qgh$$

$$P = 1000 \times (50 \times 10^{-3}) \times 9.8 \times 15$$

$$P = 7.4\,kW$$

In a **pumped storage system**, the water that flows to lower heights is pumped back to its original height by using the generators of the plant as motors to pump the water (Figure **8.11**).

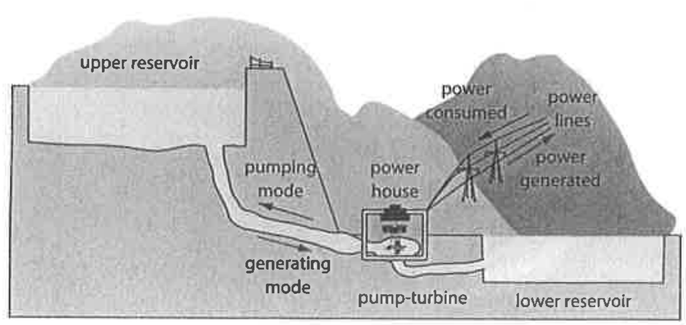


Figure 8.11 During off-peak hours water is pumped up to the higher reservoir. To do this the plant consumes electricity instead of producing it.

Obviously, to do this requires energy (more energy, in fact, than can be regained when the water is again allowed to flow to lower heights). This energy has to be supplied from other sources of electrical energy at off-peak times when the cost of electricity is low. This is the only way to **store** energy on a large scale for use when demand, and hence price, is high. In other words, cheap excess electricity from somewhere else can be provided to the plant to raise the water so that energy can be produced later when it is needed.

Figure 8.12 An array of sea-based horizontal axis wind turbines.

Wind power

This ancient method for exploiting the kinetic energy of wind is particularly useful for isolated small houses and agricultural use. Small wind turbines have vanes no larger than about 1 m long. Modern large wind turbines, with vanes larger than 30 m, are capable of producing up to a few megawatts of power (Figure **8.12**).

Wind generators produce low-frequency sound that affects some people's sleeping habits and many people find the sight of very many of them in wind parks unattractive. The blades are susceptible to stresses in high winds and damage due to metal fatigue frequently occurs. Serious power production from wind occurs at wind speeds from 6 to $14\,\mathrm{m\,s^{-1}}$. But the design must also take into account gale-force winds, which may be very rare for a particular site, but would result in damage to an inadequately designed system. About 30% of the power carried by the wind can be converted into electricity (Figure **8.13**).

Let us consider the mass of air that can pass through a tube of cross-sectional area A with velocity v in time Δt (Figure **8.14**). Let ρ be the

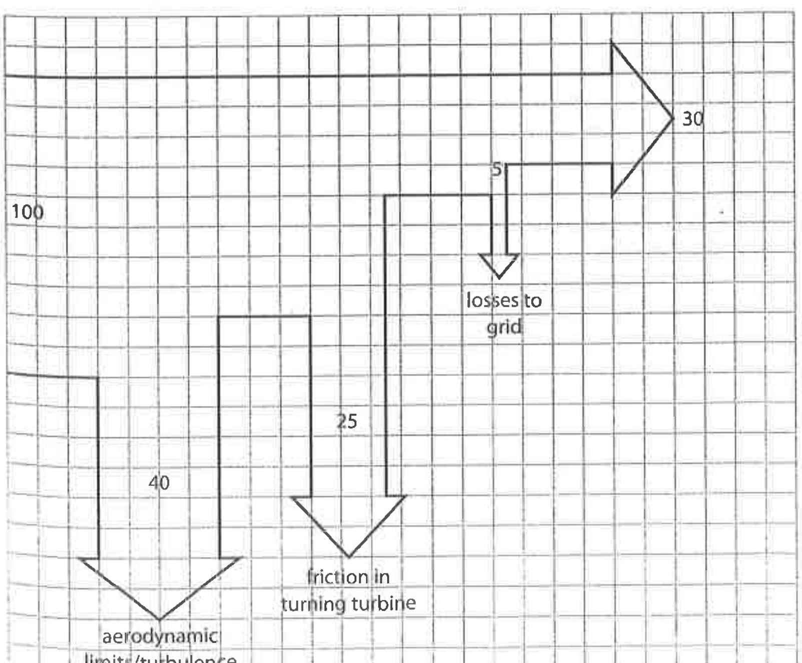


Figure 8.13 A Sankey diagram for wind energy extraction. The main loss comes from the fact the wind cannot just stop past the generator.

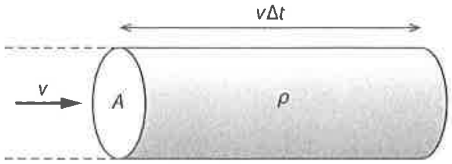


Figure 8.14 The mass of air within this cylinder will exit the right end within a time of Δt.

Exam tip: Wind power

Advantages

- 'Free'
- Inexhaustible
- Clean

Disadvantages

- Dependent on local wind conditions
- Aesthetic problems
- Noise problems

density of air. Then the mass enclosed in a tube of length $v\Delta t$ is $\rho Av\Delta t$. This is the mass that will exit the right end of the tube **within** a time interval equal to Δt. The kinetic energy of this mass of air is thus:

$$\frac{1}{2}(\rho Av\Delta t)v^2 = \frac{1}{2}\rho A\Delta tv^3$$

The kinetic energy per unit time is the power, and so dividing by Δt we find:

$$P = \frac{1}{2}\rho Av^3$$

This shows that the power carried by the wind is proportional to the cube of the wind speed and proportional to the area spanned by the blades.

Assuming a wind speed of $8.0\,\text{m}\,\text{s}^{-1}$, an air density of $1.2\,\text{kg}\,\text{m}^{-3}$ and a blade radius of 1.5 m (so area $7.1\,\text{m}^2$) we find a theoretical maximum power of:

$$P = \frac{1}{2}\rho Av^3$$

$$P = \frac{1}{2} \times 1.2 \times 7.1 \times 8.0^3$$

$$P \approx 2.2\,\text{kW}$$

Doubling the wind turbine area doubles the power extracted, but doubling the wind speed increases the power (in theory) by a factor of eight. In practice, frictional and other losses (mainly turbulence) result in a smaller power increase. The calculations above also assume that all the wind is actually **stopped** by the wind turbine, extracting all of the wind's kinetic energy. In practice this is not the case (Figure **8.15**).

Figure 8.15 The 'wake' effect created by wind as it goes past one generator affects other generators down the line, decreasing the expected power output of the windmill 'farm'.

Nature of science

Society demands action

Society's demand for ever-increasing amounts of energy raises ethical debates. How can present and future energy needs be best met, without compromising the future of the planet? There are many aspects to the energy debate, and all energy sources have associated risks, benefits and costs. Although not all governments and people support the development of renewable energy sources, scientists across the globe continue to collaborate to develop new technologies that can reduce our dependence on non-renewable energy sources.

? Test yourself

1 **a** Distinguish between specific energy and energy density of a fuel.

b Estimate the energy density of water that falls from a waterfall of height 75 m and is used to drive a turbine.

2 A power plant produces 500 MW of power.

a Determine the energy produced in one second. Express your answer in joules.

b Determine the energy (in joules) produced in one year.

3 A power plant operates in four stages. The efficiency in each stage is 80%, 40%, 12% and 65%.

a Find the overall efficiency of the plant.

b Sketch a Sankey diagram for the energy flow in this plant.

4 A coal power plant with 30% efficiency burns 10 million kilograms of coal a day. (Take the specific energy of coal to be $30\,\text{MJ}\,\text{kg}^{-1}$.)

a Calculate the power output of the plant.

b Estimate the rate at which thermal energy is being discarded by this plant.

c The discarded thermal energy is carried away by water whose temperature is not allowed to increase by more than 5 °C. Calculate the rate at which water must flow away from the plant.

5 One litre of gasoline releases 34 MJ of energy when burned. The efficiency of a car operating on this gasoline is 40%. The speed of the car is $9.0\,\text{m}\,\text{s}^{-1}$ when the power developed by the engine is 20 kW. Calculate how many kilometres the car can go with one litre of gasoline when driven at this speed.

6 A coal-burning power plant produces 1.0 GW of electricity. The overall efficiency of the power plant is 40%. Taking the specific energy of coal to be $30\,\text{MJ}\,\text{kg}^{-1}$, calculate the amount of coal that must be burned in one day.

7 In the context of nuclear fission reactors, state what is meant by:

a uranium enrichment

b moderator

c critical mass.

8 **a** Calculate the energy released in the fission reaction:

$${}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow {}^{236}_{92}\text{U} \rightarrow {}^{140}_{54}\text{Xe} + {}^{94}_{38}\text{Sr} + 2{}^{1}_{0}\text{n}.$$

(Mass data: uranium-235, ${}^{235}_{92}\text{U} = 235.043\,923\,\text{u}$; xenon-140, ${}^{140}_{54}\text{Xe} = 139.921\,636\,\text{u}$; strontium-94, ${}^{94}_{38}\text{Sr} = 93.915\,360\,\text{u}$; neutron, ${}^{1}_{0}\text{n} = 1.008\,665\,\text{u}$.)

b The power output is 200 MW. Estimate the number of fission reactions per second.

9 The energy released in a typical fission reaction involving uranium-235 is 200 MeV.

a Calculate the specific energy of uranium-235.

b Estimate how much coal (specific energy $30\,\text{MJ}\,\text{kg}^{-1}$) must be burned in order to give the same energy as that released in nuclear fission with 1 kg of uranium-235.

10 **a** A 500 MW nuclear power plant converts the energy released in nuclear reactions into electrical energy with an efficiency of 40%. Calculate how many fissions of uranium-235 are required per second. Take the energy released per reaction to be 200 MeV.

b What mass of uranium-235 is required to fission per second?

11 **a** Draw a diagram of a fission reactor, explaining the role of **i** fuel rods, **ii** control rods and **iii** moderator.

b In what form is the energy released in a fission reactor?

12 Distinguish between a solar panel and a photovoltaic cell.

13 Sunlight of intensity $700\,\text{W}\,\text{m}^{-2}$ is captured with 70% efficiency by a solar panel, which then sends the captured energy into a house with 50% efficiency.

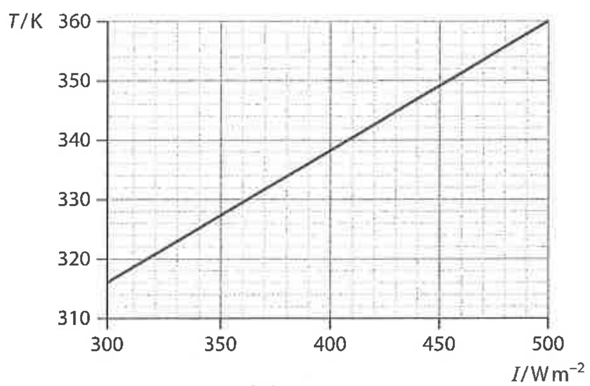
a The house loses thermal energy through bad insulation at a rate of 3.0 kW. Find the area of the solar panel needed in order to keep the temperature of the house constant.

b Draw a Sankey diagram for the energy flow from the panel to the house.

14 A solar heater is to heat 300 kg of water initially at 15 °C to a temperature of 50 °C in a time of 12 hours. The amount of solar radiation falling on the collecting surface of the solar panel is 240 W m^{-2} and is collected at an efficiency of 65%. Calculate the area of the collecting panel that is required.

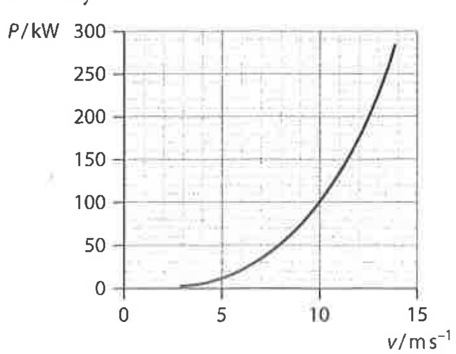
15 A solar heater is to warm 150 kg of water by 30 K. The intensity of solar radiation is 600 W m^{-2} and the area of the panels is 4.0 m^{-2}. The specific heat capacity of water is 4.2×10^3 J $kg^{-1} K^{-1}$. Estimate the time this will take, assuming a solar panel efficiency of 60%.

16 The graph shows the variation with incident solar intensity I of the temperature of a solar panel used to heat water. Thermal energy is extracted from the water at a rate of 320 W. The area of the panel is 2.0 m^2. Calculate, for a solar intensity of 400 W m^{-2}:



a the temperature of the water
b the power incident on the panel
c the efficiency of the panel.

17 The graph shows the power curve of a wind turbine as a function of the wind speed. For a wind speed of 10 m s^{-1}, calculate the energy produced in the course of one year, assuming that the wind blows at this speed for 1000 hours in the year.



18 a State the expected increase in the power extracted from a wind turbine when:
i the length of the blades is doubled
ii the wind speed is doubled
iii both the length of the blades and the wind speed are doubled.
b Outline reasons why the actual increase in the extracted power will be less than your answers.

19 Wind of speed v is incident on the blades of a wind turbine. The blades present the wind with an area A. The maximum theoretical power that can be extracted is given by:

$P = \frac{1}{2}\rho A v^3$

State the assumptions made in deriving this equation.

20 Air of density 1.2 kg m^{-3} and speed 8.0 m s^{-1} is incident on the blades of a wind turbine. The radius of the blades is 1.5 m. Immediately after passing through the blades, the wind speed is reduced to 3.0 m s^{-1} and the density of air is 1.8 kg m^{-3}. Estimate the power extracted from the wind.

21 Calculate the blade radius of a wind turbine that must extract 25 kW of power out of wind of speed 9.0 s^{-1}. The density of air is 1.2 kg m^{-3}. State any assumptions made in this calculation.

22 Find the power developed when water in a waterfall with a flow rate of 500 kg s^{-1} falls from a height of 40 m.

23 Water falls from a vertical height h at a flow rate (volume per second) Q. Deduce that the maximum theoretical power that can be extracted is given by $P = \rho Q g h$.

24 A student explaining pumped storage systems says that the water that is stored at a high elevation is allowed to move lower, thus producing electricity. Some of this electricity is used to raise the water back to its original height, and the process is then repeated. What is wrong with this statement?

25 Make an annotated energy flow diagram showing the energy changes that are taking place in each of the following:
a a conventional electricity-producing power station using coal
b a hydroelectric power plant
c an electricity-producing wind turbine
d an electricity-producing nuclear power station.

8.2 Thermal energy transfer

This section deals with the methods of heat transfer and the role of the greenhouse effect in the physical mechanisms that control the energy balance of the Earth. The important phenomenon of black-body radiation is introduced along with the associated Stefan–Boltzmann and Wien laws.

Learning objectives

- Understand the ways in which heat may be transferred.
- Sketch and interpret black-body curves.
- Solve problems using the Stefan–Boltzmann and Wien laws.
- Describe the greenhouse effect.
- Apply the Stefan–Boltzmann law to solve energy balance problems for the Earth.

Conduction, convection and thermal radiation

Heat can be transferred from place to place by three distinct methods: conduction, convection and radiation.

Imagine a solid with one end kept at a high temperature, as shown in Figure **8.16**. The electrons at the hot end of the solid have a high average kinetic energy. This means they move a lot. The moving electrons collide with neighbouring molecules, transferring energy to them and so increasing their average kinetic energy. This means that energy is being transferred from the hot to the cold side of the solid; this is **conduction**.

Collisions between electrons and molecules is the dominant way in which heat is transferred by conduction, but if there are strong bonds between molecules there is another way. Molecules on the hot side of the solid vibrate about their equilibrium positions, stretching the bonds with neighbouring molecules. This stretching forces the neighbours to also begin to vibrate, and so the average kinetic energy of the neighbours increases. Energy is again transferred.

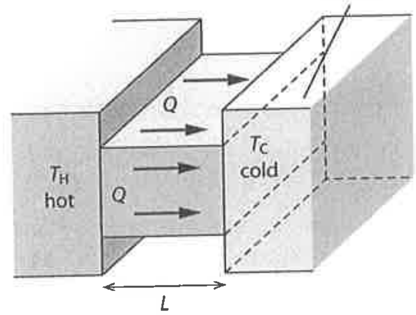


Figure 8.16 Conduction of heat through a solid as a result of a temperature difference.

For a solid of cross-sectional area A, length L and temperature difference between its ends ΔT, experiments show that the rate at which energy is being transferred is:

$$\frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{L}$$

where k is called the conductivity and depends on the nature of the substance.

Exam tip
You will not be examined on this equation.

Convection is a method of energy transfer that applies mainly to fluids, i.e. gases and liquids. If you put a pan of water on a stove, the water at the bottom of the pan is heated. As it gets hotter the water expands, it gets less dense and so rises to the top. In this way heat from the bottom of the pan is transferred to the top. Similarly, air over a hot radiator in a room is heated, expands and rises, transferring warm air to the rest of the room. Colder air takes the place of the air that rose and the process repeats, creating **convection currents**.

Both conduction and convection require a material medium through which heat is to be transferred. The third method of heat transfer, **radiation**, does not. Energy from the Sun has been warming the Earth for billions of years. This energy arrives at Earth as radiation having travelled through the vacuum of space at the speed of light. Radiation is such an important part of climate and the energy balance of the Earth that we treat it in a separate section.

Black-body radiation

One of the great advances in physics in the 19th century was the discovery that all bodies that are kept at some **absolute** (kelvin) temperature T radiate energy in the form of electromagnetic waves. This is radiation created by oscillating electric charges in the atoms of the body. The power radiated by a body is governed by the **Stefan–Boltzmann law**.

The amount of energy per second (i.e. the power) radiated by a body depends on its surface area A and the absolute temperature of the surface T:

$$P = e\sigma AT^4$$

This is known as the Stefan–Boltzmann law. The constant σ is known as the Stefan–Boltzmann constant and equals $\sigma = 5.67 \times 10^{-8}\,\mathrm{W\,m^{-2}\,K^{-4}}$.

The constant e is known as the **emissivity** of the surface. Its value is between 0 and 1; it measures how effectively a body radiates. When $e = 1$ we call the body a **black body**. This is a theoretical body; it is a perfect radiator as well as a perfect absorber. A black body will absorb all the radiation falling upon it, reflecting none. This does sound somewhat strange, but a black body at low temperature radiates very little and absorbs all the radiation falling on it so it looks black. At high temperature it radiates a lot and looks very bright. A very good example of this is a piece of charcoal. A real body is a good approximation to the theoretical black body if its surface is black and dull.

Consider a body of emissivity e and surface temperature T whose surroundings have a temperature T_s and may be assumed to be a black body. The body radiates at a rate $e\sigma AT^4$ and absorbs at a rate $e\sigma AT_s^4$. The *net rate* at which energy leaves the body is therefore:

$$P_{net} = e\sigma AT^4 - e\sigma AT_s^4$$

$$P_{net} = e\sigma A(T^4 - T_s^4)$$

At equilibrium no net power leaves the body and so $T = T_s$, as we might expect. Table **8.3** gives values for the emissivity of various surfaces.

The energy radiated by a body is electromagnetic radiation and is distributed over an infinite range of wavelengths. However, most of the energy is radiated at a specific wavelength λ_{max} that is determined by the temperature of the body:

$$\lambda_{max} T = 2.90 \times 10^{-3}\,\mathrm{K\,m}$$

This is known as **Wien's displacement law**.

Surface	Emissivity
black body	1
ocean water	0.8
ice	0.1
dry land	0.7
land with vegetation	0.6

Table 8.3 Emissivity of various surfaces.

Worked example

8.7 A human body has temperature 37 °C, the average Earth surface temperature is 288 K and the temperature of the Sun is 5800 K. In each case, calculate the peak wavelength of the emitted radiation.

We just have to apply Wien's law, $\lambda_{max}T = 2.90 \times 10^{-3}$ K m, and make sure we use kelvins in each case. So:

human body: $\lambda_{max} = \frac{2.90 \times 10^{-3}}{273+37} \approx 9 \times 10^{-6}$ m, an infrared wavelength.

Earth surface: $\lambda_{max} = \frac{2.90 \times 10^{-3}}{288} \approx 1 \times 10^{-5}$ m, an infrared wavelength.

Sun: $\lambda_{max} = \frac{2.90 \times 10^{-3}}{5800} \approx 5 \times 10^{-7}$ m, visible light that determines the colour of the Sun.

Figure **8.17** shows how the intensity of radiation emitted from the same surface changes as the temperature of the surface is varied ($T = 350$ K, 300 K and 273 K). We see that, with increasing temperature, the peak of the curve occurs at lower wavelengths and the height of the peak increases.

Figure **8.18** shows the intensity distribution of radiation from various different surfaces kept at the same temperature (300 K). The difference in the curves is due to the different emissivities ($e = 1.0$, 0.8 and 0.2). The curves are identical apart from an overall factor that shrinks the height of the curve as the emissivity decreases.

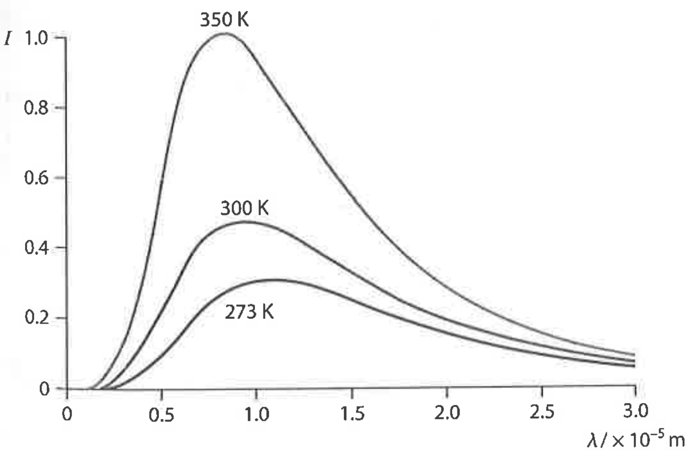


Figure 8.17 Black-body spectra for a body at the three temperatures shown. The units on the vertical axis are arbitrary. (The curves appear to start from a finite value of wavelength. This is not the case. The curves start at zero wavelength but are too small to appear on the graphs.)

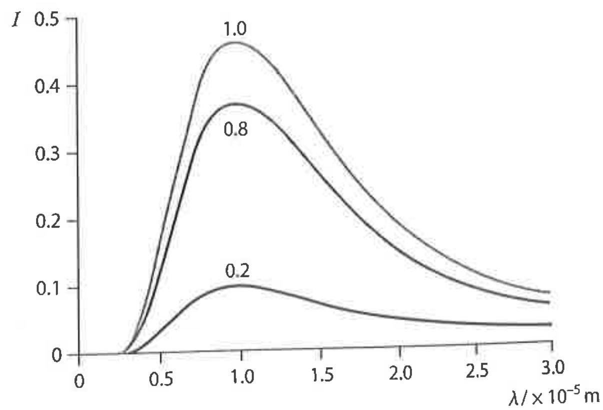


Figure 8.18 The spectra of three bodies with different emissivities at the same temperature (300 K). The units on the vertical axis are arbitrary.

Worked examples

8.8 By what factor does the power emitted by a body increase when the temperature is increased from 100 °C to 200 °C?

The temperature in kelvin increases from 373 K to 473 K. Since the emitted power is proportional to the fourth power of the temperature, power will increase by a factor:

$$\left(\frac{473}{373}\right)^4 = 2.59$$

8.9 The emissivity of the naked human body may be taken to be $e = 0.90$. Assuming a body temperature of 37 °C and a body surface area of 1.60 m^2, calculate the total amount of energy lost by the body when exposed to a temperature of 0.0 °C for 30 minutes.

The net power lost is the difference between the power emitted by the body and the power received. Let the body temperature be T_1 and the temperature of the surroundings be T_2. Then:

$$P_{net} = e\sigma A(T_1^4 - T_2^4)$$

Substituting the values from the question:

$$P_{net} = 0.90 \times 5.67 \times 10^{-8} \times 1.60 \times (310^4 - 273^4)$$

$$P_{net} = 301\ \text{W}$$

Exam tip
Make sure the temperature is in kelvin.

So the energy lost in time t seconds is:

$$E = P_{net}t$$

$$E = 301 \times 30 \times 60$$

$$E = 5.4 \times 10^5\ \text{J}$$

(What does this mean for the human body? For the purposes of an estimate, assume that the body has mass 60 kg and is made out of water, with specific heat capacity $c = 4200\ \text{J kg}^{-1}\text{K}^{-1}$. This energy loss would result in a drop in body temperature of $\Delta T = \frac{5.4 \times 10^5}{60 \times 4200} = 2.1$ K. This would be serious! However, it ignores the fact that respiration provides a source of energy.)

The solar constant

The Sun may be considered to radiate as a perfect emitter (i.e. as a black body). The Sun emits a total power of about $P = 3.9 \times 10^{26}$ W. The average Earth–Sun distance is $d = 1.50 \times 10^{11}$ m. Imagine a sphere of this radius centred at the Sun. The power of the Sun is distributed over the area of this sphere and so the power per unit area, i.e. the **intensity**, received by Earth is:

$$I = \frac{P}{4\pi d^2}$$

Intensity is the power of radiation received per unit area.

Substituting the numerical values gives:

$$I = \frac{3.9 \times 10^{26}}{4\pi(1.50 \times 10^{11})^2} \approx 1400\ \text{W m}^{-2}$$

This is the intensity of the solar radiation at the top of the Earth's atmosphere. It is called the **solar constant** and is denoted by S.

If we know that radiation of intensity I is incident on a surface of area A, we can calculate the **power** delivered to that area from:

$$P = IA$$

Albedo

The **albedo** (from the Latin for 'white'), α, of a body is defined as the ratio of the power of radiation scattered from the body to the total power incident on the body:

$$\alpha = \frac{\text{total scattered power}}{\text{total incident power}}$$

The albedo is a dimensionless number. Snow has a high albedo (0.85), indicating that snow reflects most of the radiation incident on it, whereas charcoal has an albedo of only 0.04, meaning that it reflects very little of the light incident on it. The Earth as a whole has an average global albedo that is about 0.3. The albedo of the Earth varies. The variations depend on the time of the year (many or few clouds), latitude (a lot of snow and ice or very little), on whether one is over desert land (high albedo, 0.3–0.4), forests (low albedo, 0.1) or water (low albedo, 0.1), etc.

The calculation of the solar constant as $S = 1400\,\mathrm{W\,m^{-2}}$ is the value at the upper atmosphere. The radiation that reaches the Earth has to go through the area of a disc of radius R. The power through this disc is therefore:

$$P = S\pi R^2$$

where R is the radius of the Earth (Figure **8.19**). The albedo of the Earth is α, and so a fraction $\alpha S\pi R^2$ of the incident power is reflected, leaving $(1-\alpha)S\pi R^2$ to reach Earth. Clearly, the Earth's surface receives radiation during the day, when it faces the Sun. But if we want to define a night and day average of the incident intensity I_{av} we must divide the power through the disc by the total surface area of the Earth to get:

$$I_{av} = \frac{(1-\alpha)S\pi R^2}{4\pi R^2}$$

$$I_{av} = \frac{(1-\alpha)S}{4}$$

This average intensity amounts to $\frac{0.7 \times 1400}{4} = 245\,\mathrm{W\,m^{-2}}$.

In other words, at any moment of the day or night, anywhere on Earth, one square metre of the surface may be thought to receive 245 J of energy every second.

Exam tip
The solar constant S is intensity. Intensity is power per unit area so:

$$P = SA$$

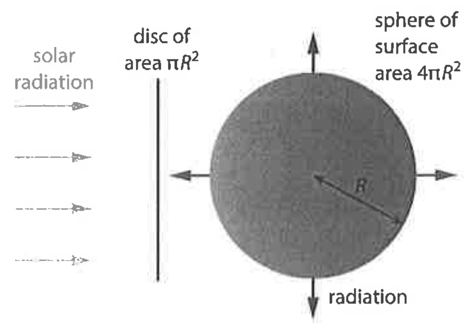


Figure 8.19 The radiation reaching the Earth must first go through a disc of area πR^2, where R is the radius of the Earth.

Energy balance

We are interested in the average temperature of the Earth. If this temperature is constant then the energy input to the Earth must equal (balance) the energy output by the Earth (Figure **8.20**).

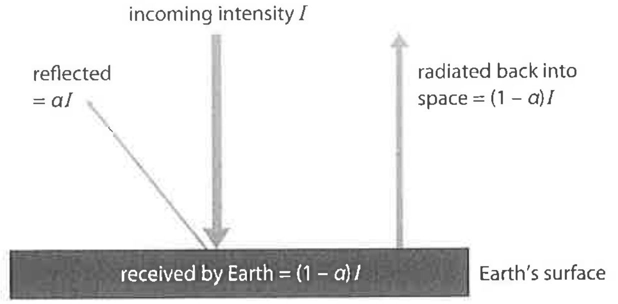


Figure 8.20 Energy diagram showing energy transfers in a model without an atmosphere. Note that the energy in equals the energy out.

The next worked example introduces a first glimpse of an **energy balance equation**.

Worked example

8.10 Assume that the Earth surface has a fixed temperature T and that it radiates as a black body. The average incoming solar radiation reaching the surface has intensity $I_{av} = \frac{(1-\alpha)S}{4} = 245\ \mathrm{W\,m^{-2}}$. Ignore the effect of the atmosphere (other than the fact that is has reflected 30% of the incoming radiation back into space!).

a Write down an equation expressing the fact that the power received by the Earth equals the power radiated by the Earth into space (an energy balance equation).

b Solve the equation to calculate the constant Earth temperature.

c Comment on your answer.

a The average intensity reaching the surface is:

$$I_{av} = \frac{(1-\alpha)S}{4} = 245\ \mathrm{W\,m^{-2}}$$

The Earth radiates power from the entire surface area of its spherical shape, and so the power radiated, P_{out} (by the Stefan–Boltzmann law), is:

$$P_{out} = \sigma A T^4$$

(Here we are assuming that the Earth is a black body, so $e = 1$ and the surrounding space is taken to have a temperature of 0 K.) So the intensity radiated by the Earth, I_{out}, is:

$$I_{out} = \frac{P_{out}}{A} = \sigma T^4$$

Equating the incident and outgoing intensities we get:

$$\frac{(1-\alpha)S}{4} = \sigma T^4$$

b Solving the equation, we find:

$$T = \sqrt[4]{\frac{(1-\alpha)S}{4\sigma}}$$

This evaluates to:

$$T = \sqrt[4]{\frac{245}{5.67 \times 10^{-8}}} = 256\,\text{K}$$

This temperature is −17 °C.

c It is perhaps surprising that this extremely simple model has given an answer that is not off by orders of magnitude! But a temperature of 256 K is 32 K lower than the Earth's average temperature of 288 K, and so obviously the model is too simplistic. One reason this model is too simple is precisely because we have not taken into account the fact that not all the power radiated by the Earth actually escapes. Some of the power is absorbed by the gases in the atmosphere and is re-radiated back down to the Earth's surface, causing further warming that we have neglected to take into account. In other words, this model neglects the greenhouse effect. This simple model also points to the general fact that increasing the albedo (more energy reflected) results in lower temperatures.

Another drawback of the simple model presented above is that the model is essentially a zero-dimensional model. The Earth is treated as a point without interactions between the surface and the atmosphere. (Latent heat flows, thermal energy flow in oceans through currents, thermal energy transfer between the surface and the atmosphere due to temperature differences between the two, are all ignored.) Realistic models must take all these factors (and many others) into account, and so are very complex.

The greenhouse effect

The Earth's surface radiates as all warm bodies do. But the Earth's surface is at an average temperature of 288 K and, using Wien's law, we saw in Worked example **8.7** that the peak wavelength at which this energy is radiated is an infrared wavelength. Unlike visible light wavelengths, which pass through the atmosphere mainly unobstructed, infrared radiation is strongly absorbed by various gases in the atmosphere, the so-called **greenhouse gases**. This radiation is in turn re-radiated by these gases in all directions. This means that some of this radiation is received by the Earth's surface again, causing additional warming (Figure **8.21**).

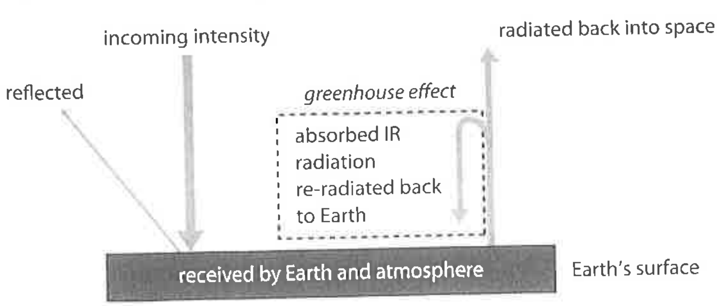


Figure 8.21 A simplified energy flow diagram to illustrate the greenhouse effect.

This is radiation that would be lost in space were it not for the greenhouse gases. Without this **greenhouse effect**, the Earth's temperature would be 32 K lower than what it is now.

The greenhouse effect may be described as the warming of the Earth caused by infrared radiation, emitted by the Earth's surface, which is absorbed by various gases in the Earth's atmosphere and is then partly re-radiated towards the surface. The gases primarily responsible for this absorption (the greenhouse gases) are water vapour, carbon dioxide, methane and nitrous oxide.

The greenhouse effect is thus a **natural** consequence of the presence of the atmosphere. There is, however, also the **enhanced** greenhouse effect, which refers to additional warming due to **increased** quantities of the greenhouse gases in the atmosphere. The increases in the gas concentrations are due to human activity.

The main greenhouse gases are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Greenhouse gases in the atmosphere have natural as well as man-made (anthropogenic) origins (Table **8.4**). Along with these sources of the greenhouse gases, we have 'sinks' as well, that is to say, mechanisms that reduce these concentrations. For example, carbon dioxide is absorbed by plants during photosynthesis and is dissolved in oceans.

Greenhouse gas	Natural sources	Anthropogenic sources
H_2O	evaporation of water from oceans, rivers and lakes	irrigation
O_2	forest fires, volcanic eruptions, evaporation of water from oceans	burning fossil fuels in power plants and cars, burning forests
CH_4	wetlands, oceans, lakes and rivers, termites	flooded rice fields, farm animals, processing of coal, natural gas and oil, burning biomass
N_2O	forests, oceans, soil and grasslands	burning fossil fuels, manufacture of cement, fertilisers, deforestation (reduction of nitrogen fixation in plants)

Table 8.4 Sources of greenhouse gases.

Mechanism of photon absorption

As for atoms, the energy of molecules is discrete. There are energy levels corresponding to the energy of molecules due to their vibrational and rotational motion. The difference in energy between molecular energy levels is approximately the energy of an infrared photon. This means that infrared photons travelling through greenhouse gases will be absorbed. The gas molecules that have absorbed the photons will now be excited to higher energy levels. But the molecules prefer to be in low-energy states, and so they immediately make a transition to a lower-energy state by emitting the photons they absorbed. But these photons are not all emitted outwards into space. Some are emitted back towards the Earth, thereby warming the Earth's surface (Figure **8.22**).

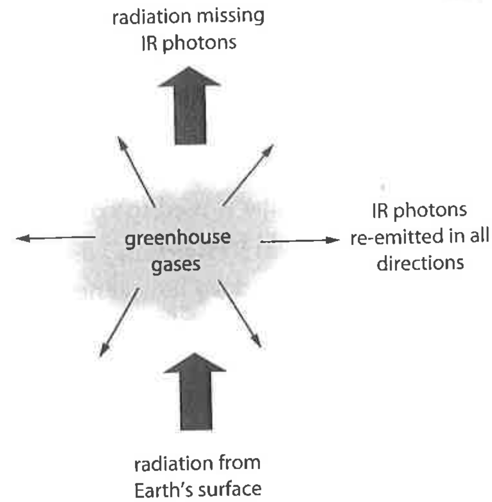


Figure 8.22 Greenhouse gases absorb infrared (IR) photons and re-radiate them in all directions.

Worked example

8.11 One consequence of warming of the Earth is that more water will evaporate from the oceans. Predict whether this fact alone will tend to increase the temperature of the Earth further or whether it will tend to reduce it.

Evaporating means that energy must be supplied to water to turn it into vapour and so this energy will have to come from the atmosphere, reducing its temperature. Further, there will be more cloud cover, so more solar radiation will be reflected back into space, further reducing temperatures. This is an example of negative feedback: the temperature increases for some reason but the effect of this increase is a tendency of the temperature to decrease and not increase further. (There is, however, another factor of **positive feedback** that will tend to increase temperatures: evaporating water means that the carbon dioxide that was dissolved in the water will now return to the atmosphere!) To decide the overall effect, detailed calculations are necessary. (Negative feedback wins in this case.)

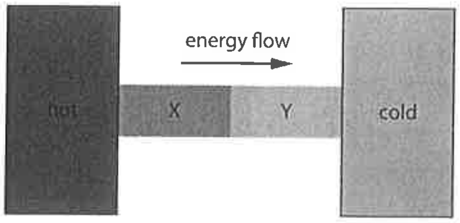
Nature of science

Simple and complex modelling

In Topic **3** we met the kinetic theory of gases. This simple mathematical model can predict the behaviour of real gases to a good approximation. By contrast, to reach reliable predictions about climate change and its consequences, very complex and time-consuming modelling is required. Models for climate behaviour are complex because of the very large number of parameters involved, the interdependence of these parameters on various kinds of feedback effects and the sensitivity of the equations on the initial values of the parameters. This makes predictions somewhat less certain than we would like. Advances in computing power, the availability of more data and further testing and debate on the various models will improve our ability to predict climate change more accurately in the future.

Test yourself

26 A cylindrical solid tube is made out of two smaller tubes, X and Y, of different material. X and Y have the same length and cross-sectional area. The tube is used to conduct energy from a hot to a cold reservoir.



State and explain whether the following are equal or not:

a the rates of flow of energy through X and Y

b the temperature differences across X and Y.

27 Suggest whether there is any point in using a ceiling fan in winter.

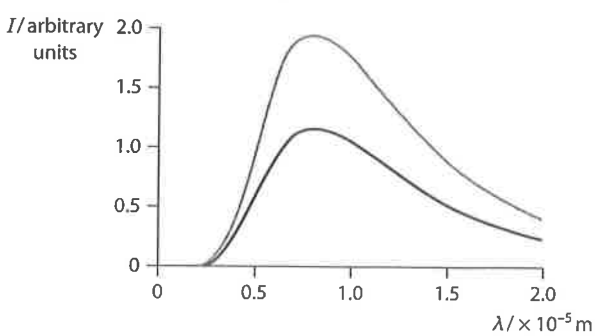
28 Calculate the ratio of the power radiated per unit area from two black bodies at temperature 900 K and 300 K.

29 a State what you understand by the term **black body.**

b Give an example of a body that is a good approximation to a black body.

c By what factor does the rate of radiation from a body increase when the temperature is increased from 50 °C to 100 °C?

30 The graph shows the variation with wavelength of the intensity of radiation emitted by two bodies of identical shape.



a Explain why the temperature of the two bodies is the same.

b The upper line corresponds to a black body. Calculate the emissivity of the other body.

31 The total power radiated by a body of area $5.00\,\text{km}^2$ and emissivity 0.800 is 1.35×10^9 W. Assume that the body radiates into a vacuum at temperature 0 K. Calculate the temperature of the body.

32 Assume that the distance d between the Sun and the Earth decreases. Then the Earth's average temperature T will go up. The fraction of the power radiated by the Sun that is received on Earth is proportional to $\frac{1}{d^2}$; the power radiated by the Earth is proportional to T^4.

a Deduce the dependence of the temperature T of the Earth on the distance d.

b Hence estimate the expected rise in temperature if the distance decreases by 1.0%. Take the average temperature of the Earth to be 288 K.

33 **a** Define the term **intensity** in the context of radiation.

b **Estimate** the intensity of radiation emitted by a naked human body of surface area $1.60\,\text{m}^2$, temperature 37 °C and emissivity 0.90, a distance of 5.0 m from the body.

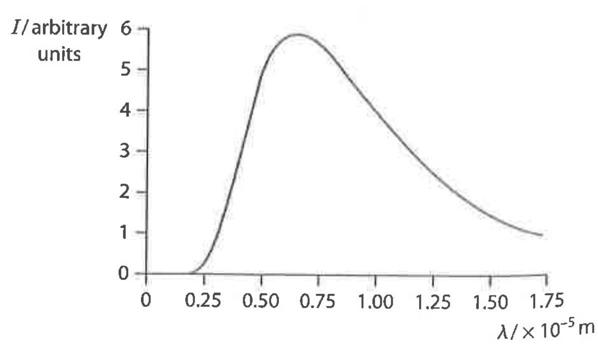
34 A body radiates energy at a rate (power) P.

a Deduce that the intensity of this radiation at distance d from the body is given by:

$$I = \frac{P}{4\pi d^2}$$

b State **one** assumption made in deriving this result.

35 The graph shows the variation with wavelength of the intensity of the radiation emitted by a black body.



a Determine the temperature of the black body.

b Copy the diagram and, on the same axes, draw a graph to show the variation with wavelength of the intensity of radiation emitted by a black body of temperature 600 K.

36 a Define the term **albedo**.

b State **three** factors that the albedo of a surface depends on.

37 a State what is meant by the **greenhouse effect**.

b State the main greenhouse gases in the Earth's atmosphere, and for each give **three** natural and **three** man-made sources.

38 A researcher uses the following data for a simple climatic model of an Earth without an atmosphere (see Worked example **8.10**): incident solar radiation = 350 W m^{-2}, absorbed solar radiation = 250 W m^{-2}.

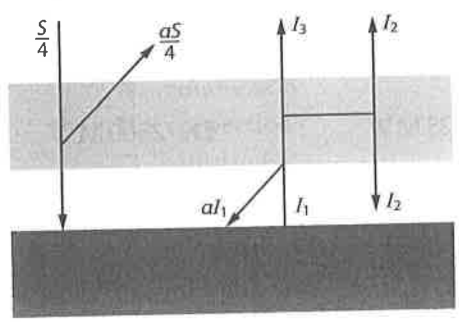
a Make an energy flow diagram for these data.

b Determine the average albedo for the Earth that is to be used in the modelling.

c Determine the intensity of the outgoing long-wave radiation.

d Estimate the temperature of the Earth according to this model, assuming a constant Earth temperature.

39 The diagram shows a more involved model of the greenhouse effect.



Exam tip

You will not get anything as complicated as this in the exam, but this is excellent practice in understanding energy balance equations.

The average incoming radiation intensity is $\frac{S}{4} = 350\,\text{W m}^{-2}$. The albedo of the atmosphere is 0.300. Assume that only a fraction t of the energy radiated by the Earth actually escapes the Earth and that the surface behaves as a black body. The model assumes that part of the radiation from the Earth is reflected back down from the atmosphere.

a The intensity radiated by the Earth is I_1, the intensity radiated by the atmosphere is I_2 and the fraction of the intensity escaping the Earth is I_3. By examining the energy balance of the atmosphere and the surface separately, show that:

$$I_1 = \frac{2}{1-\alpha+t} \times \frac{(1-\alpha)S}{4},$$

$$I_2 = \frac{1-\alpha-t}{1-\alpha+t} \times \frac{(1-\alpha)S}{4} \quad \text{and}$$

$$I_3 = \frac{2t}{1-\alpha+t} \times \frac{(1-\alpha)S}{4}$$

b Show that as much energy enters the Earth–atmosphere system as leaves it.

c Show that a surface temperature of $T \approx 288\,\text{K}$ implies that $t = 0.556$.

d i Explain why the emissivity of the atmosphere is $1 - t - \alpha$.

ii Calculate the temperature of the atmosphere.

40 Outline the main ways in which the surface of the Earth loses thermal energy to the atmosphere and to space.

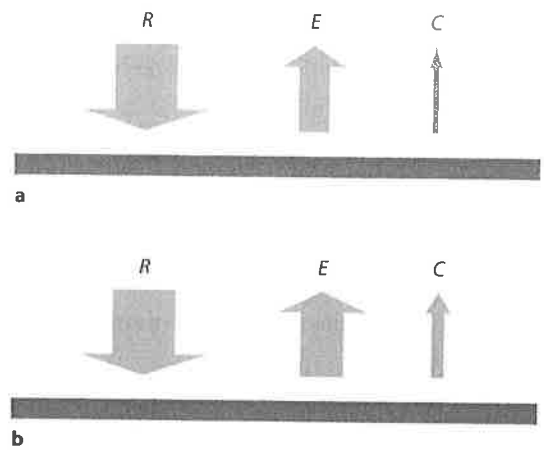
41 a Compare the albedo of a subtropical, warm, dry land with that of a tropical ocean.

b Suggest mechanisms through which the subtropical land and the tropical ocean lose thermal energy to the atmosphere.

c If the sea level were to increase, sea water would cover dry land. Suggest **one** change in the regional climate that might come about as a result.

42 Evaporation is a method of thermal energy loss. Explain whether you would expect this method to be more significant for a tropical ocean or an arctic ocean.

43 The diagram shows two energy flow diagrams for thermal energy transfer to and from specific areas of the surface of the Earth. R represents the net energy incident on the surface in the form of radiation, E is the thermal energy lost from the Earth due to evaporation, and C is the thermal energy conducted to the atmosphere because of the temperature difference between the surface and the atmosphere.
Suggest whether the Earth area in each diagram is most likely to be dry and cool or moist and warm.



44 It is estimated that a change of albedo by 0.01 will result in a 1 °C temperature change. A large area of the Earth consists of 60% water and 40% land. Calculate the expected change in temperature if melting ice causes a change in the proportion of the area covered by water from 60% to 70%. Take the albedo of dry land to be 0.30 and that of water to be 0.10.

Exam-style questions

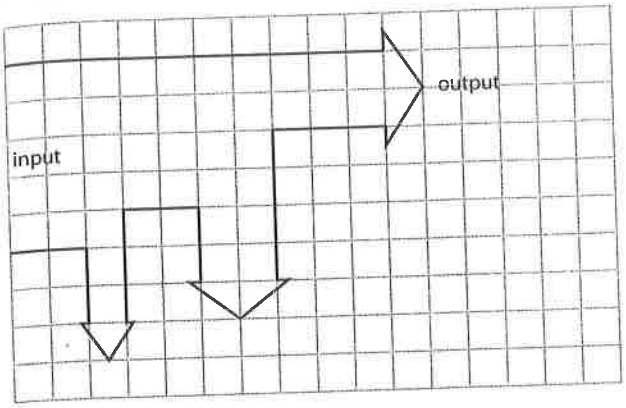
1 A power plant produces 500 MW of electrical power with an overall efficiency of 20%. What is the input power to the plant?

A 100 MW B 400 MW C 625 MW D 2500 MW

2 The specific energy of a fuel is the:

A energy that can be extracted from a unit volume of the fuel
B energy that can be extracted from a unit mass of the fuel
C energy contained in a unit volume of the fuel
D energy contained in a unit mass of the fuel.

3 What is the efficiency of a system whose Sankey diagram is shown below?



A 10% B 20% C 30% D 40%

4 Which of the following lists contains one renewable and one non-renewable source of power?

A uranium, coal
B natural gas, biomass
C wind power, wave power
D hydropower, solar power

5 A plastic ruler and a metallic ruler are in the same room. The metallic ruler 'feels' colder when touched. What is the reason for this?

A Plastic has a lower specific heat capacity than metal.
B Plastic has a higher specific heat capacity than metal.
C Plastic is a better conductor of heat than metal
D Plastic is a worse conductor of heat than metal.

6 A fireplace warms a room by:

A conduction
B convection
C radiation
D conduction, convection and radiation

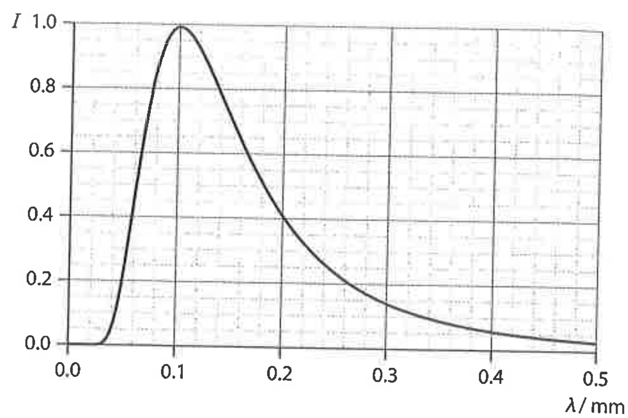
7 A star explodes in the vacuum of space. The thermal energy transferred by the star takes place through:

A radiation B conduction C convection D evaporation

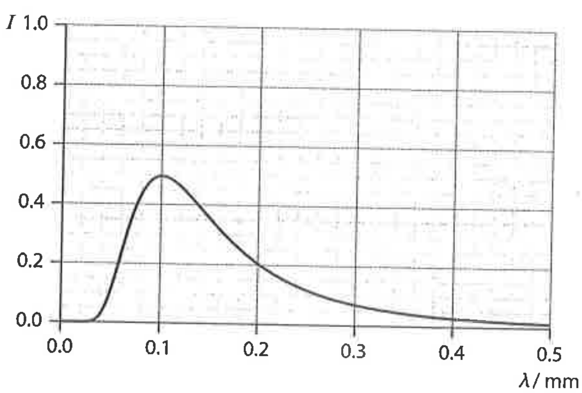
8 Four different rooms are losing energy to the outside through a wall. The temperature difference between the inside and the outside of the rooms is the same. Which combination of wall area and wall thickness results in the smallest rate of heat loss?

	Area	**Thickness**
A	S	d
B	$2S$	$\frac{d}{2}$
C	S	$2d$
D	$2S$	$2d$

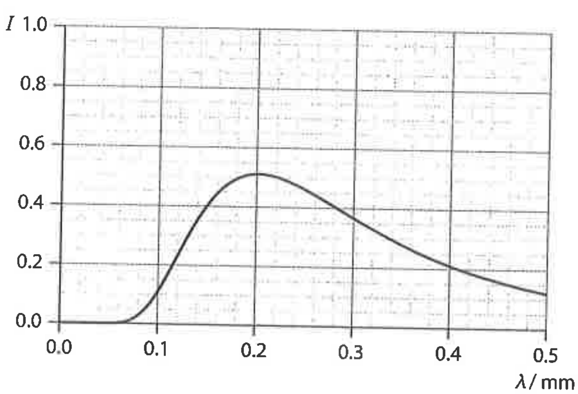
9 The graph shows the variation with wavelength of the intensity from a unit area of a black body. The scale on the vertical axis on all graphs in this question is the same.



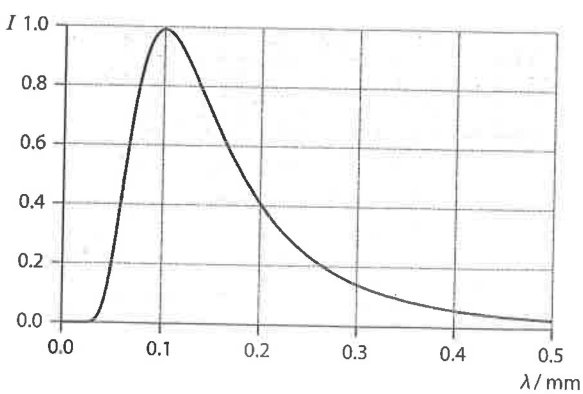
The area and the temperature of the black body are both halved. Which graph now shows the correct variation with wavelength of the intensity from a unit area of the body?



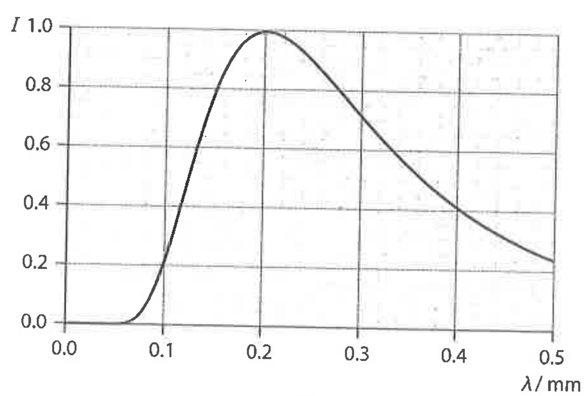
A



B

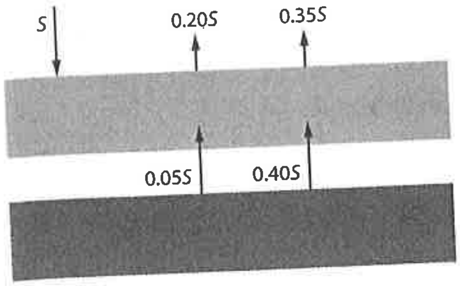


C



D

0 The intensity of solar radiation incident on a planet is S. The diagram represents the energy balance of the planet. The atmosphere reflects an intensity 0.20S and radiates 0.35S. The surface reflects 0.05S and radiates 0.40S.



What is the albedo of the planet?

A 0.05 **B** 0.20 **C** 0.25 **D** 0.60

11 A nuclear power plant produces 800 MW of electricity with an overall efficiency of 0.32. The fission reaction taking place in the core of the reactor is:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2^{1}_{0}n$$

a **i** Using the masses provided below show that the energy released in one fission reaction is about 180 MeV. [2]

$^{1}_{0}n = 1.009\,u$, $^{235}_{92}U = 235.044\,u$, $^{140}_{54}Xe = 139.922\,u$, $^{94}_{38}Sr = 93.915\,u$.

ii Estimate the specific energy of uranium-235. [2]

iii Show that the mass of uranium-235 undergoing fission in one year is about 1500 kg. [3]

b In a nuclear fission reactor, describe the role of:

i the moderator [2]

ii the control rods [2]

iii the heat exchanger. [2]

c Suggest what might happen to a nuclear fission reactor that does not have a moderator. [2]

d State **one** advantage and **one** disadvantage of nuclear power. [2]

12 In a pumped storage system, the high reservoir of water has area $4.8 \times 10^4\,m^2$ and an average depth of 38 m. When water from this reservoir falls to the lower reservoir the centre of mass of the water is lowered by a vertical distance of 225 m. The water flows through a turbine connected to a generator at a rate of $350\,m^3\,s^{-1}$.

a Calculate the mass of the water in the upper reservoir. [1]

b Determine the loss of gravitational potential energy when the upper reservoir has been completely emptied. [2]

c Estimate the power supplied by the falling water. [2]

The efficiency of the plant in converting this energy into electricity is 0.60. The price of electricity sold by this power station at peak times is $0.12 per kW h. The plant can buy off-peak electrical power at $0.07 per kW h. The efficiency at which water can be pumped back up to the high reservoir is 0.64.

d Estimate the profit made by the power plant for a single emptying and refilling of the high reservoir. [3]

13 a Outline, in the context of a wind turbine, the meaning of **primary** and **secondary** energy. **[2]**

b The power that can be theoretically extracted by a wind turbine of blade radius R in wind of speed v is $P_{max} = \frac{1}{2}\pi\rho R^2 v^3$

i State **one** assumption that has been made in deriving this expression. **[1]**

ii Explain **one** other reason why the actual power derived from the wind turbine will be less than P_{max}. **[2]**

c A wind turbine has an overall efficiency of 0.30. The following data are available:

Density of air entering turbine = $1.2\,\text{kg}\,\text{m}^{-3}$

Density of air leaving turbine = $1.9\,\text{kg}\,\text{m}^{-3}$

Speed of air entering turbine = $8.2\,\text{m}\,\text{s}^{-1}$

Speed of air leaving turbine = $5.3\,\text{m}\,\text{s}^{-1}$

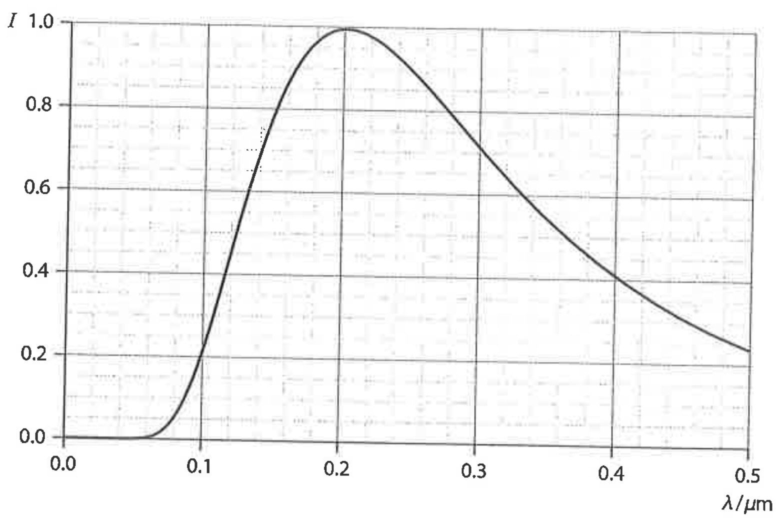
Blade radius = 12 m

Estimate the power extracted by this wind turbine. **[3]**

14 a On a hot summer day there is usually a breeze from the sea to the shore. Explain this observation. **[3]**

b Explain why walking on a day when the temperature is 22 °C would be described as very comfortable but swimming in water of the same temperature would be described as cool. **[2]**

A black body has temperature T. The graph shows the variation with wavelength of the intensity of radiation emitted by a unit area of the body. The units on the vertical axis are arbitrary.



c **i** Describe what is meant by a **black body**. **[2]**

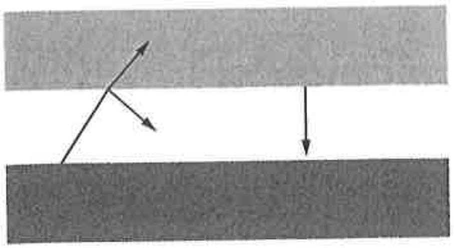
ii Estimate T. **[2]**

d On a copy of the axes above sketch a graph to show the variation with wavelength of the intensity of radiation emitted by a unit area of:

i a grey body of emissivity 0.5 and temperature T (label this graph G) **[2]**

ii a black body of temperature $\frac{2T}{3}$ (label this graph B). **[2]**

15 The diagram shows a black body of temperature T_1 emitting radiation towards a grey body of lower temperature T_2 and emissivity e. No radiation is transmitted through the grey body.



a Using all or some of the symbols T_1, T_2, e and σ, state expressions for the intensity:

i radiated by the black body [1]

ii radiated by the grey body [1]

iii absorbed by the grey body [1]

iv reflected by the grey body. [1]

b The black and the grey bodies in **a** gain as much energy as they lose. Deduce that their temperatures must be the same. [2]

16 The power radiated by the Sun is P and the Earth–Sun distance is d. The albedo of the Earth is α.

a i Deduce that the solar constant (i.e. the intensity of the solar radiation) at the position of the Earth is $S=\frac{P}{4\pi d^2}$ [2]

ii State what is meant by **albedo**. [1]

b i Explain why the average intensity absorbed by the Earth surface is $\frac{S(1-\alpha)}{4}$ [3]

ii $P=3.9\times10^{26}$ W, $d=1.5\times10^{11}$ m and $\alpha=0.30$. Assuming the Earth surface behaves as a black body, estimate the average equilibrium temperature of the Earth. [2]

c The average Earth temperature is much higher than the answer to **b ii**. Suggest why this is so. [3]